SURF@IFISC 2023 Proposals

1. Stochastic thermodynamics and information

Advisor: Gonzalo Manzano

In the last two decades, thermodynamics has been extended to describe small systems, where the action of environmental noise “blurs” traditional thermodynamic constraints and information plays a central role [1]. While the first law of thermodynamics (aka energy conservation) holds at the microscale, the second law becomes more subtle and is manifested on a statistical level, through the emergence of a set of universal nonequilibrium fluctuation relations that may take the form of both equalities or inequalities. Stochastic thermodynamics can be applied to a number of systems ranging from molecular motors acting inside the cell, to synthetic electronic and quantum devices interacting with mesoscopic environments. In this project we will explore different aspects of the thermodynamic description of small systems and their link with information theory, including microscopic models of Maxwell’s demon though experiment and the use of gambling strategies for stopping a process at particularly selected times [2].

[1] J. M. R. Parrondo, J. M. Horowitz, and T. Sagawa, *Thermodynamics of information,* Nature Physics 11, 131–139 (2015).
[2] G. Manzano, D. Subero, O. Maillet, R. Fazio, J. P. Pekola, and É. Roldán, *Thermodynamics of Gambling Demons*, Physical Review Letters 126, 080603 (2021).

2. Semiconductor laser network dynamics with inhomogeneous elements

Advisors: Apostolos Argyris and Miguel C. Soriano

Large-scale coupled laser networks with all-to-all connectivity have demonstrated generalized and clustered synchronization through chaotic signals, depending on the network size and the coupling conditions of its elements. Here we will investigate numerically the impact of considering laser elements with inhomogeneous properties and different network coupling motifs. We will validate the synchronization capabilities of the networks, evaluating the complexity of the emission signals under which they become synchronized.

3. Compartmental models and their application to study phytopathologies

Advisor: Manuel A. Matías

Compartmental models (e.g. the SIR model) have a long history and have been crucial in understanding aspects of epidemic transmission, like the existence of infection thresholds. The project will consist in the application of different versions of these models to epidemic transmission among plants, typically carried out by insects (vectors). The models will be applied to diseases recently generated by the bacterium Xylella fastidiosa on several hosts (vines, almond-trees, olive-trees,…), for which real data are available.

The project requires both numerical (Python or Julia are preferred, but compiled languages like C or Fortran are acceptable) and analytical skills

4. Optimizing Quantum Thermal Machines: Investigating the Role of Coherence, Entanglement and Information Flow
Advisor: Rosa López

We propose to investigate the use of quantum systems in thermal devices, as they have been shown to be more efficient at converting heat to work than classical systems. Specifically, we will study the thermodynamic and kinetic uncertainty relations, which allow for a reduction in the noise-to-power ratio without increasing entropy production or system activity. This research will also examine the impact of coherence and entanglement on quantum conductors in relation to these uncertainty relations. Furthermore, we will investigate the use of a Maxwell demon feedback mechanism to understand how information flow is affected by these uncertainty relations. The ultimate goal of this study is to inform the optimal design and implementation of quantum thermal machines in future quantum technologies.

5. Power grid stability in scenarios of large renewable penetration
Advisor: Pere Colet

The power grid is, arguably, the largest socio-technical system in the world. Stable operation requires the synchronization of the power plants and a precise balance between generation and consumption. The balance is not easy to achieve due to the random character of (part of) the load and the increasing use of renewable sources which are subject to uncontrollable factors, such as wind or sunlight. In this project we will study the synchronization and stability of a prototypical power grid when a large fraction of the generation comes from renewable sources, as well as the effect of including battery storage systems.

6. Quantifying higher-order interactions in social systems
Advisor: Sandro Meloni

Networks, through the tools offered by Network Science, represent a fundamental framework for research in socio-technological systems, allowing the study of both their structural organization and its effects on the dynamics of social interactions. However, despite the huge success in explaining different collective phenomena [1], increasing evidence [2,3] suggests that a representation based solely on dyadic (i.e. pairwise) interactions may overlook some critical features of social dynamics. Specifically, it has been shown [2,3] that multi-body or group interactions may play a pivotal role in shaping social behavior. This highlighted the importance of considering interactions whose effects on the dynamics of the system cannot be represented as a combination of pairwise relationships (usually labeled as Higher-Order Interactions or HOIs) into the study of social dynamics. A first step in assessing the relevance of HOIs for the modeling of social systems will be to detect and quantify the presence of group interactions in social systems and this is the aim of this proposal. The vast majority of datasets covering social interactions both from online social networks or in-person close contacts (e.g. [4]) are represented as dyadic interactions. However, this may be an artifact of the collection method, where genuine group interactions are split in pairwise relationships. Thus, the objective of this proposal is to analyze available datasets (e.g.[4,5]) to detect group interactions in social systems. To do that, theoretical and inference frameworks like the one in [6] will be used. Finally, a systematic classification of core social groups and their temporal evolution will be provided.

[1} C. Castellano, S. Fortunato, V. Loreto. Statistical physics of social dynamics, Rev. Mod. Phys. 81, 592 (2009)
[2] F. Battiston, G. Cencetti, I. Iacopini, V. Latora, M. Lucas, A. Patania, J.-C. Young and G. Petri. Networks beyond pairwise interactions: structure and dynamics. Phys. Rep. 874 1–92 (2020).
[3] R. Lambiotte, M. Rosvall and I. Scholtes. From networks to optimal higher- order models of complex systems Nat. Phys. 15 313–20 (2019).
[4] Sociopatterns collaboration http://www.sociopatterns.org/
[5] V. Sekara, A. Stopczynski and S. Lehmann. Fundamental structures of dynamic social networks. 13 (36) 9977-9982 (2016).
[6] J.-G. Young, G. Petri, T.P. Peixoto. Hypergraph reconstruction from network data. Comm. Phys. 4, 1 (2021).

7. Optimisation of aircraft trajectories
Advisor: Massimiliano Zanin

Aircraft trajectories obtained from public sources suffer from multiple problems. Firstly, due to technical limitations, position reports may be erroneous or not realistic - an aircraft may be detected over Spain, 30 seconds later over Germany, and then again over Spain; clearly the second point is wrong. Secondly, the trajectory of a same aircraft may be available from different sources, which could be combined to obtain a better estimation. Thirdly, even if a trajectory is ok, one may want to create “virtual points” between existing position reports, to artificially improve the temporal resolution of the data. In this project we will tackle this problem, by developing a software library able to merge and pre-process trajectory data coming from different sources, and by relying on a data set comprising all flights crossing Europe since 2018. The starting point will be functions assessing how "reliable" a given trajectory point is, and by optimising this value by moving it in a 4D space. The student must have a good knowledge of Python and of its standard libraries; previous experience in data analysis, especially over large quantities of data, will also positively be evaluated.